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WEAPON CHAMBER PRESSURE MEASUREMENT

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Extensive testing, at pressure levels from 34 to 758 MPa (5,000 to 110,000 PSI) was done at Aberdeen Proving Ground to evaluate 15 different types of electrical pressure transducers used in large caliber weapons. When using a given type of transducer, the ability to consistently distinguish dynamic pressure variations as small as 0.2% was demonstrated. Yet different models of pressure transducers disagree by as much as 2%.

I. BACKGROUND

Measurements of pressure inside large caliber weapons are critical for establishing the balance between crew safety and combat effectiveness. A 2% error in chamber pressure measurement can result in a 3% change in weight, a 4% change in effective range, and a 6% change in fatigue life.

A study of electrical pressure transducers used to measure large caliber weapon chamber pressure was conducted at Aberdeen Proving Ground from January 1979 to March 1982. Extensive testing, at pressure levels from 34 to 758 MPa (5,000 to 110,000 PSI) was done to evaluate 15 different types of pressure transducers.

Tests to evaluate bias between readings from different types of transducers as well as the variability of readings produced by a single type of transducer were conducted. In the laboratory, both dynamic and static pressure readings were made. In the field, a 175mm gun was used to evaluate differences in transducer performance.

II. CHAMBER PRESSURE INSTRUMENTATION

Peak chamber pressure can be measured mechanically with "crusher gages" or electrically with electrical pressure transducers. Although this paper does not address mechanical measurement, M-11 copper crusher gages were used in conjunction with electrical transducers in many of the dynamic tests.

In this study, 2 to 4 samples each of 10 types of piezoelectric and 5 strain type transducers were obtained. Figure 1 shows several of the different transducers. Of the 15 types tested, 8 were commercially manufactured and 7 were fabricated by various US Army proving grounds or laboratories.

To facilitate changing from one type of transducer to another, all transducers were housed in an adapter 3.2cm in diameter and 8cm long. This procedure not only made changing transducers practical, it allowed

recognition of a discrepancy between the static and dynamic performance of a miniature transducer caused by an installation problem.

A technique to be avoided if at all possible, is the installation of a miniature transducer directly into a large caliber gun tube. This practice presents two problems. First, a workpiece as big as a large caliber gun tube presents a number of challenges to the machinist, which can lead to dimensional, alignment, or surface finish errors. Second, there is no way to test the transducer in place to see if an installation problem has occurred.

It is preferable to mount the transducer in a small adapter that can be accurately machined. Then the transducer-adapter assembly can be checked both dynamically and statically before field testing begins.

For many years, the typical instrument used to record chamber pressure measurements has been the FM analog tape recorder. These instruments typically have a frequency response of 40 to 80 kHz, which is well above the 5 to 10 kHz response normally required for large caliber chamber pressure waveforms. Analog tape recorders usually have a signal to noise ratio of 100:1 and 1% linearity. The digital data acquisition system and computer controlled signal conditioning used in this study has an absolute accuracy of better than 0.3% and resolution to better than 0.1%.

III. LINEARITY TESTING

Linearity testing was done by measuring transducer output from 34.5 MPa to 483 MPa (5,000 to 70,000 PSI) in steps of 34.5 MPa. At each pressure level, three readings were made. Pressure was supplied by a dead weight pressure balance accurate to better than 0.1%.

The worst case results are shown in Figure 2. Note that this is a plot of <u>peak</u> nonlinearity. For the 11 most promising transducers, the <u>mean</u>, nonlinearity is only 0.3% of full scale over the entire range. This error can be further reduced by limiting analysis to only the expected pressure range of a particular test (e.g., 350 to 450 MPa only).

IV. TESTING FOR VARIATION

It is important that a transducer read consistently from shot to shot, since variability of the transducer cannot normally be distinguished from variability of the ammunition being tested. During the testing for variation phase, estimates of the within-gage variation (WGV) and gage-to-gage variation (GGV) were obtained.

Assume that the output of a given pressure transducer follows the mathematical model:

$$X = P_A + \beta + \Delta + \varepsilon$$

where

X = Reading obtained from transducer
P_A = Actual pressure
β = Bias of transducer (constant for all readings)
Δ = Variability of transducer (random variable)
ε = Experimental error (random variable)

It is assumed that β is a property that varies from one transducer to another (i.e., from one serial number to another) and also varies from one model of transducer to another (e.g., from model A to model B). For any one transducer, however, β is assumed to be constant.

Tests were conducted in this study to find the following quantities:

Within-gage variation (WGV). This quantity is a measure of the variation that would be observed if the same transducer is subjected to the exact same pressure over and over. It is the standard deviation of the random variable Δ of a single gage in the mathematical model above.

Gage-to-gage variation (GGV). This quantity is a measure of the variation that would be observed when changing from one transducer to another of the same type (i.e., same model, different serial number). It is a measure of the difference between the β's of two gages.

Gage model bias. This quantity is the systematic bias that is observed when changing from one model of transducer to another (e.g., from model A to model B).

Comparison of the transducers under dynamic conditions was done using the hydrodynamic pressure generator shown in Figure 3. A large mass or slug is driven by compressed air and strikes a piston in the high pressure hydraulic system. When the slug strikes the piston, a high pressure pulse ($\sim$6 milliseconds duration) is produced in an oil filled chamber. This chamber can accommodate four electrical transducers and four M-11 copper crusher gages. This device is used to develop the relationship between copper sphere deflection and pressure level that is presented in copper crusher gage tarage tables.

For each type of transducer, 4 samples were placed in the ports of the hydrodynamic generator. Ten shots were fired at a pressure level of approximately 379 MPa (55,000 PSI). The static test for variation was done using a dead weight pressure balance with 4 ports at a pressure level of 310 MPa (45,000 PSI).

The results are presented graphically in Figures 4 and 5. In each figure a ratio is shown (1.38 for WGV and 3.05 for GGV). This ratio represents a difference that is significant at the .05 level.

Consider the WGV data presented in Figure 4. This characteristic is relatively small (typically 0.05%) for all transducers and essentially the same value under both dynamic and static conditions.

GGV appears to be the larger component of transducer variability. Note that GGV is generally greater than WGV and dynamic GGV is generally larger than static GGV. The mean static GGV observed was 0.25%. The mean dynamic GGV observed was .41%.

V. TESTING FOR BIAS

This phase of testing was conducted to see if one type of transducer consistently read higher than another. It should be noted that there is no technique known that will produce a calibrated dynamic pressure pulse with whose amplitude is both accurate and traceable to the National Bureau of Standards. The only type of pressure that is accurate and traceable is static pressure.

Because of this problem a "majority rules" kind of logic is required when analyzing differences between transducer measurements under dynamic conditions. That is, if most transducers read one pressure level, and one or two read significantly different, it is assumed that the majority reading is the "correct" value and the outliers are "wrong". In fact, there is no way of determining which reading is "correct" and which reading is "wrong" unless the differences are very large.

The first test for bias was conducted using a 175mm gun. The gun tube was drilled for installation of pressure transducers at four locations as shown in Figure 6.

Testing for bias was conducted using only the 11 most promising transducers. Because all 11 types of transducers could not be tested at once, a balanced incomplete block test plan was used. An 11 by 2 plan requires 55 shots to permit each transducer to be tested with every other type of transducer. Two replications of this plan, for a total of 110 shots were conducted. The sequence of shots was randomized.

In shots 1 and 2, for example, two Model D transducers are placed in one set of forward and rear positions, and two Model K transducers are placed in the other set of forward and rear positions. This arrangement permits comparison of the transducers in two rear positions and comparison of the two forward positions.

Because the pressure level of each shot is slightly different and a given transducer is only used on certain shots, it is not appropriate to compare the simple mean output of the various types of transducers. Reference 1 describes the technique used to correct for shot-to-shot pressure variations by calculation of the "treatment effect" of each transducer. These "treatment effects" are estimates of the means which would have been observed if all transducers had been used in every shot.

To contrast static effects with dynamic effects, the same 110 shot sequence was repeated using the dead weight pressure balance at 50,000 PSI (344.75 MPa). Four transducers are tested at a time, two of one model versus two of another model. Ideally, all four transducers should agree with one another and indicate 50,000 PSI.

The final test for bias was conducted using the hydrodynamic pressure generator. Once again, the randomized 110 shot sequence was followed.

In the hydrodynamic generator, all four electrical transducers should agree with one another. In addition to the electrical transducers, four M-11 mechanical copper crusher gages were used in each shot. Because the hydrodynamic generator is used to develop the tarage tables for the M-11, the mechanical readings should agree very well with the electrical readings.

Figure 7 is a comparison of the three different tests for bias. All tests were conducted in the 275 to 350 MPa region (40,000 to 50,000 PSI) and are plotted on roughly the same scale. The quantity W represents a difference that is significant at the .05 level.

Note that the quantity W (which can also be considered as an indicator of experimental error) and the extreme spread (ignoring outliers) of the results essentially double when moving from static conditions to dynamic conditions. Error and extreme spread essentially double again when moving from laboratory conditions (hydrodynamic generator) to field conditions (175mm gun). Finally, note that the extreme spread (ignoring outliers) of estimated treatment effects differ by more than 2%.

These observations illustrate the need for both laboratory and field testing of pressure transducers. Laboratory testing is important for establishing suitability of transducers and identifying outliers. It is also usually more accurate than field testing.

The acceleration and thermal characteristics of the hydrodynamic generator, however, are not the same as those of a large caliber weapon. Field testing, therefore, is and always will be the final determining factor for establishing the suitability of a transducer. Because field testing is almost an order of magnitude more expensive than laboratory testing, it would seem prudent that transducers used on critical tests should be tested both statically and dynamically in the laboratory before being used in the field.

VI. HIGH PRESSURE TESTING

The effort to increase firepower and improve weapon performance has resulted in increasing levels of chamber pressure. These higher levels present a variety of new measurement challenges. A limited amount of testing was conducted at the 700 MPa (102,000 PSI) pressure level.

Static testing was done using a controlled clearance dead weight pressure balance at 689 MPa (100,000 PSI). Dynamic testing was done using a newly acquired dynamic pressure generator which produced pulses of approximately 3 milliseconds duration. No field testing was done because of the extreme expense of the ammunition required ($2000 per round).

Both the static and dynamic facilities were limited to 2 transducers per shot. Balanced incomplete block tests for bias were conducted using the 7 transducers capable of operating at this pressure level.

The static test required 21 static pressure readings. The results are shown in Figure 8. Only 5 electrical transducers performed satisfactorily during the dynamic test. The analysis of the 10 shots using those 5 transducers is shown in Figure 8 also.

Note that the extreme spread of electrical transducer treatment effects is approximately 0.5% both statically and dynamically. A difference of ~0.5% between static treatment effects is significant at the .05 level. Yet a difference of more than 2% between dynamic treatment effects is required to obtain the same level of significance.

VII. LATIN SQUARE TESTING

A Latin square test was conducted to determine if any bias existed between the four electrical transducer locations in the hydrodynamic pressure generator. An enhancement of a classical Latin square test plan was used to obtain additional precision through replication.

In a classical Latin square test of four locations (ref. 1), four shots would be required, using a different configuration for each shot. The enhanced plan uses three shots in each configuration, as shown in Figure 9, for a total of 12 shots.

This entire sequence was conducted once using four tourmaline transducers and a second time using four miniature quartz transducers for a grand total of 24 shots. Analysis of all 24 shots as well as analysis of the quartz transducer data in groups of 4 shots each indicated that the difference between the four positions was not significant at the .05 level.

Analysis of the 12 shots done with the tourmaline transducer produced an interesting observation of the precision of dynamic pressure measurements. These shots were analyzed as three separate tests of four shots each as shown in Figure 10. Note that the difference between the top positions (A & D) and the bottom positions becomes more pronounced as one moves from the first shot in each configuration to the last shot in that same configuration.

Note that by the third shot in a given configuration (i.e., shots 3, 6, 9, and 12) a small, but clearly significant difference exists between the top positions and the bottom positions. It is assumed that this small effect (0.16% of reading) is caused by the packing grease flowing out of the transducers in the top positions. While conducting the test, it was observed that after three shots, the original packing grease remained in the bottom tourmaline transducers, but was gone from the top transducers.

The important fact to be remembered is not the observation that "grease runs downhill"! The important observation is that a significant difference as small as 0.16% can be discerned from dynamic pressure measurements.

Such precision is only possible when a powerful analytical approach, such as the Latin square test, is used. The Latin square analysis removes transducer model bias (2%), shot-to-shot variation (3%), and gage-to-gage variation (.4%) to obtain high precision.

Hence, this level of precision (0.16%) should not be confused with absolute accuracy. It should, however, serve as a goal for future improvement of measurement accuracy.

VIII. CONCLUSIONS

The results of this study present the science of chamber pressure measurement with a dilemma. When using a given type of transducer, the ability to distinguish variations of dynamic pressure as small as 0.2% from experimental error was demonstrated. Yet different models of pressure transducers disagree in field testing by as much as 2%. Before any dramatic improvement in the accuracy of chamber pressure measurement can be made, the transducer model bias problem must be solved.

As mentioned previously, there is no way of knowing which type of transducer is "correct" and a "majority rules" kind of logic has been used in this study. A technique for developing a calibrated (traceable to the National Bureau of Standards ± 0.5%) pressure pulse with an appropriate magnitude, rise time, and duration is needed.

REFERENCE

Natrella, Mary Gibbons; Experimental Statistics; National Bureau of Standards Handbook 91, Issued 1 August 1963; US Government Printing Office, Washington, DC.

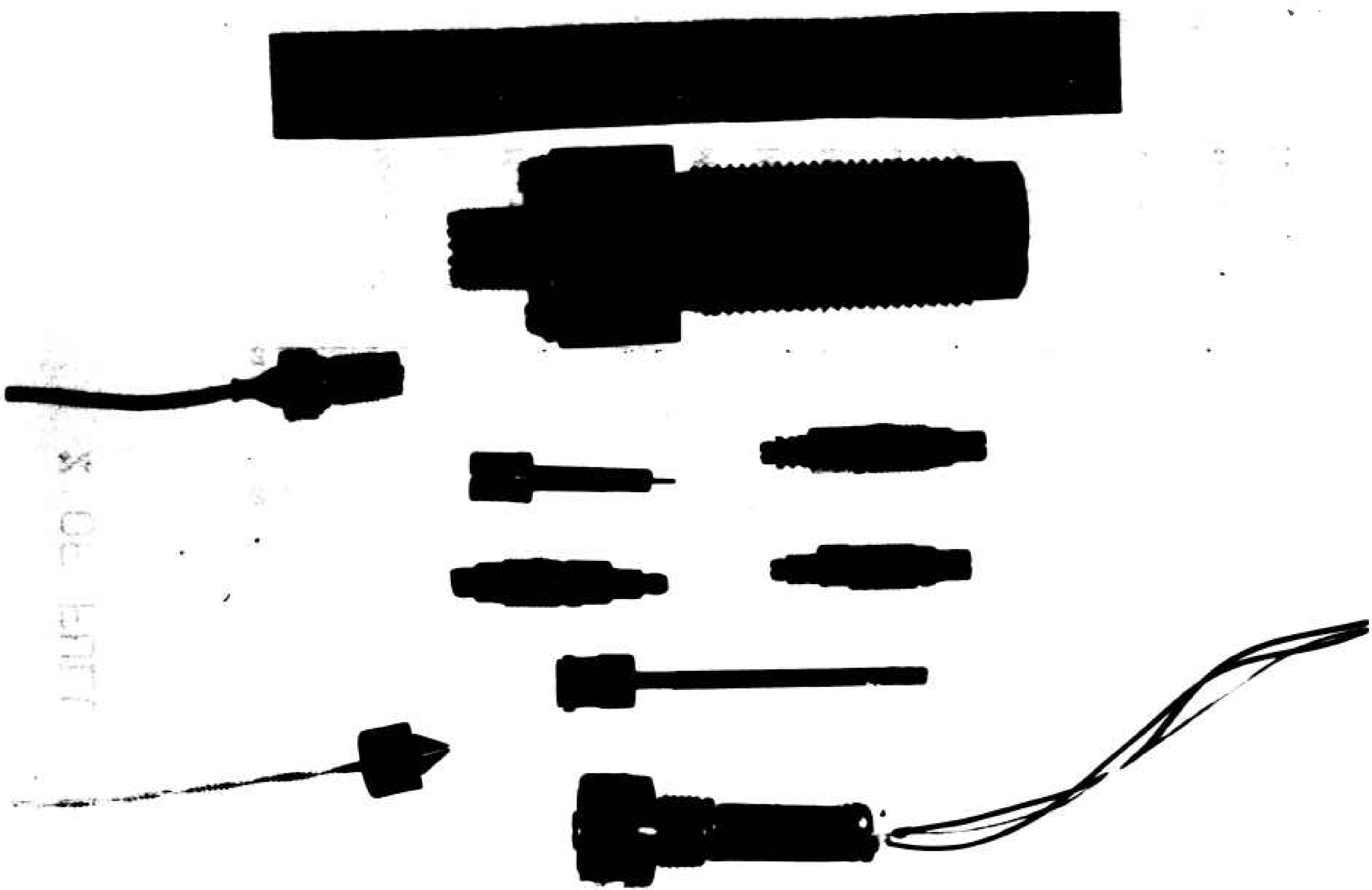


Figure 1. Photograph of several different types of pressure transducers used in this study.

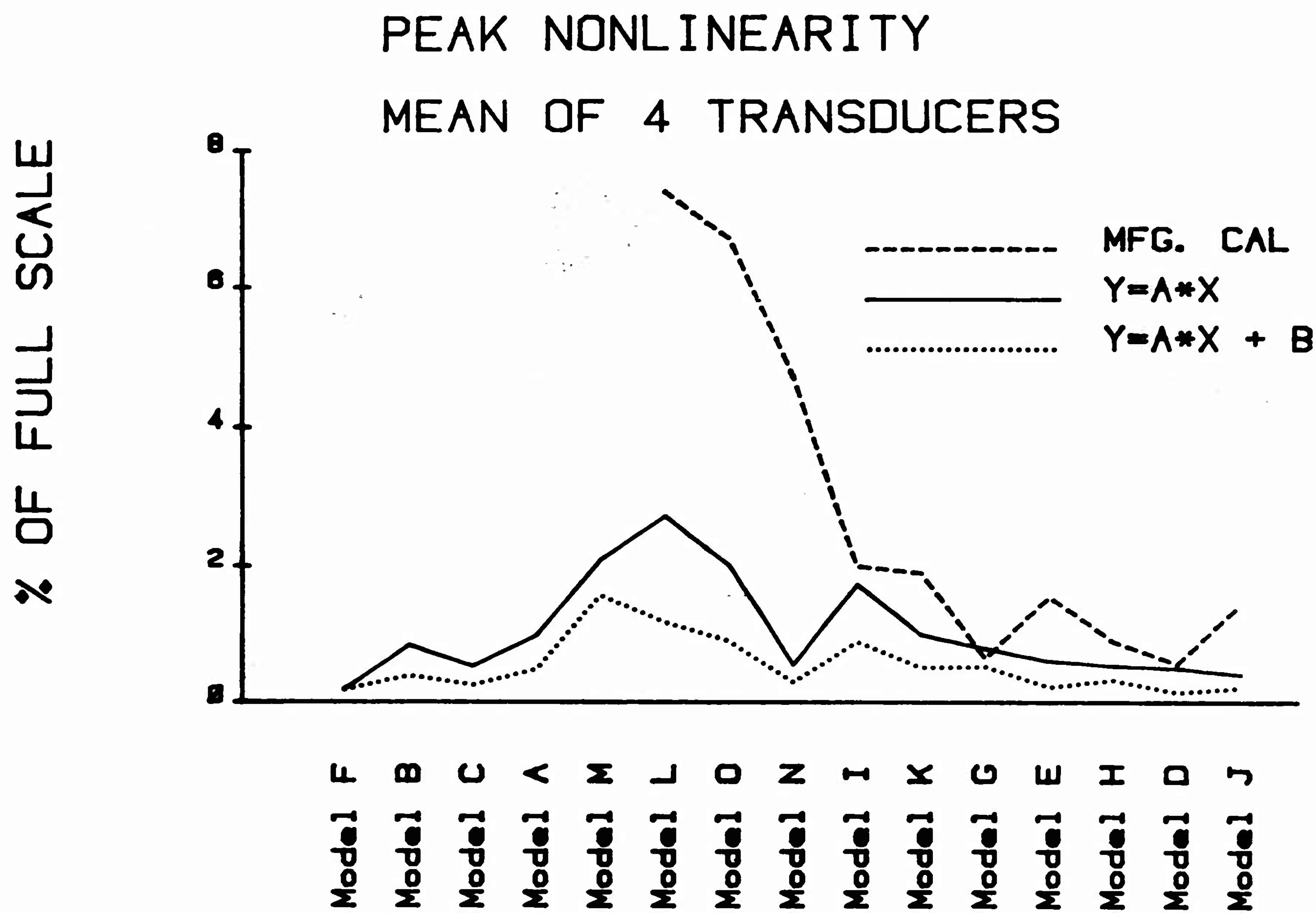
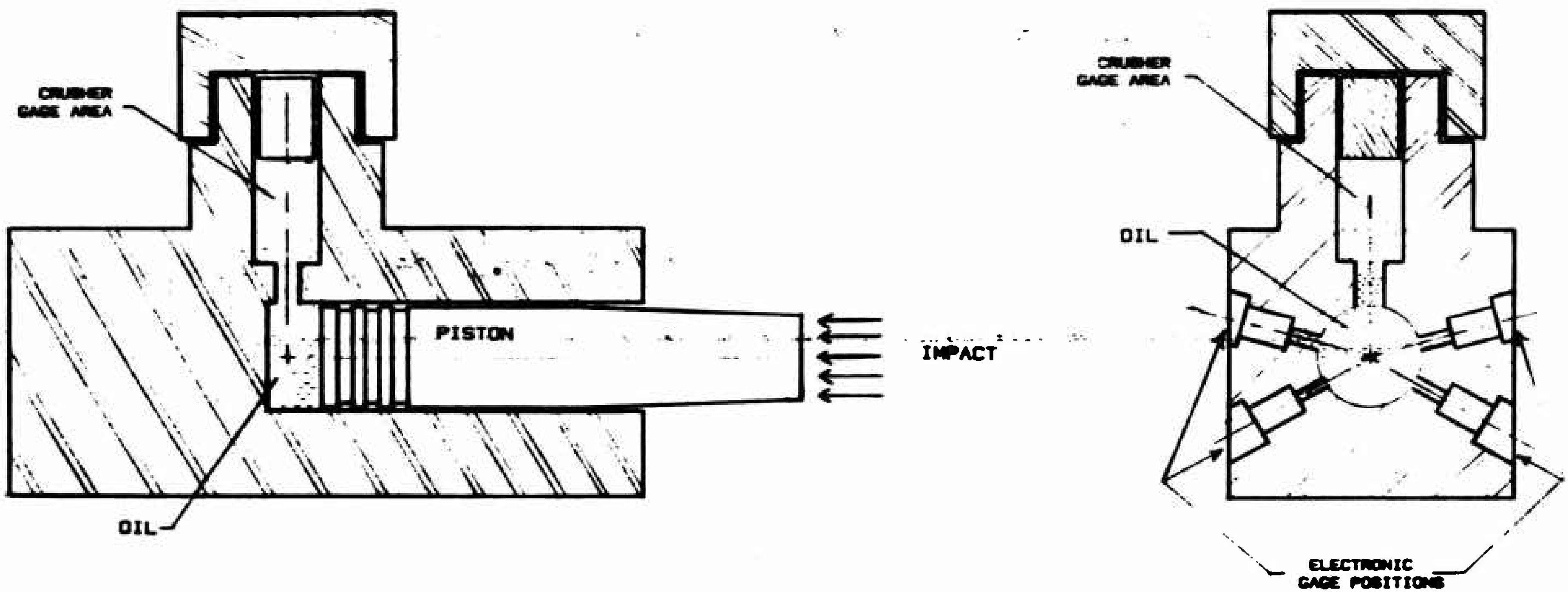


Figure 2. Comparison of several measures of linearity performance of 15 types of pressure transducers.



HYDRODYNAMIC
PRESSURE GENERATOR

Figure 3. Schematic diagram of hydrodynamic pressure generator.

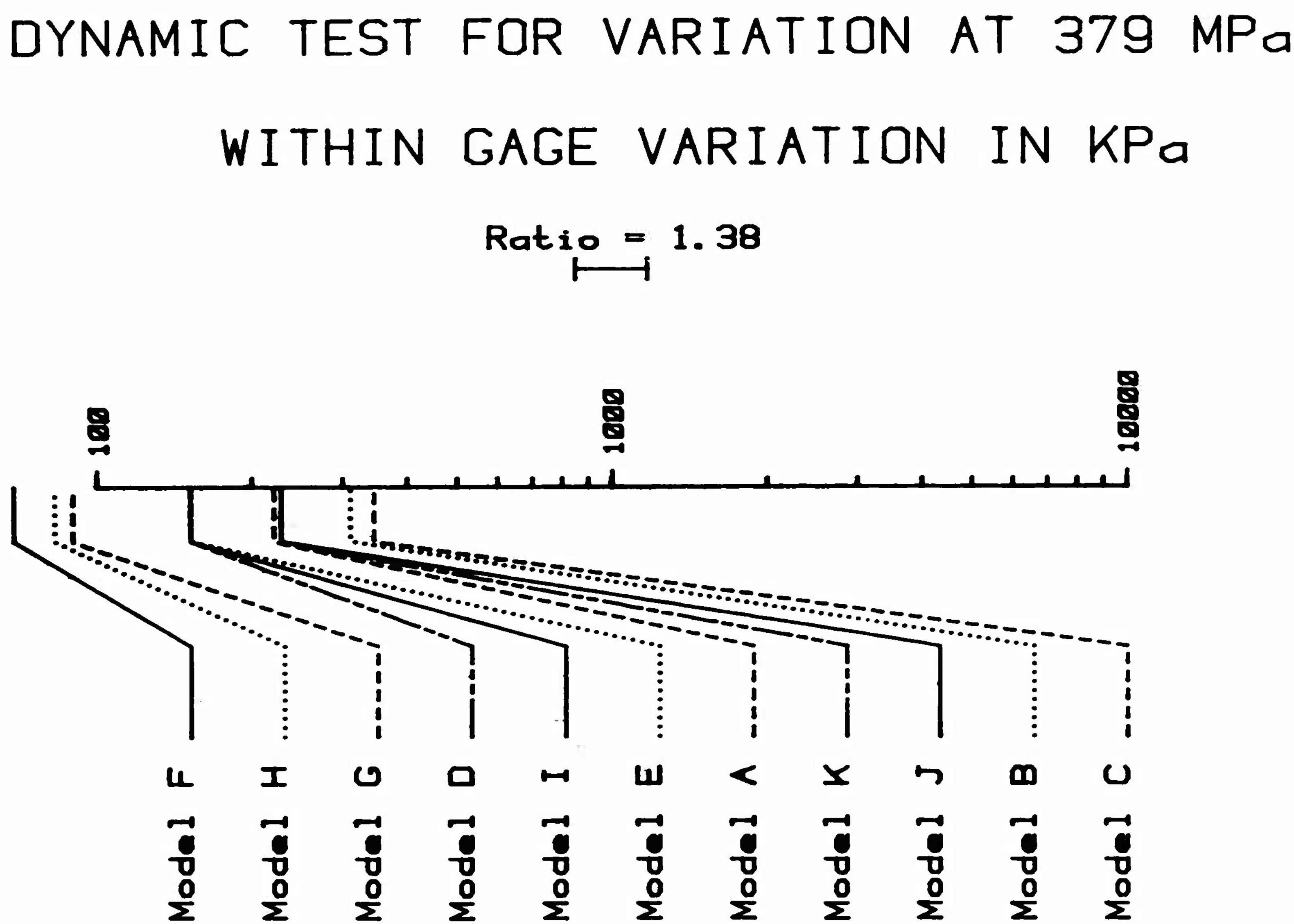


Figure 4A. Comparison of static to dynamic WGV.

STATIC TEST FOR VARIATION AT 310 MPa

WITHIN GAGE VARIATION IN KPa

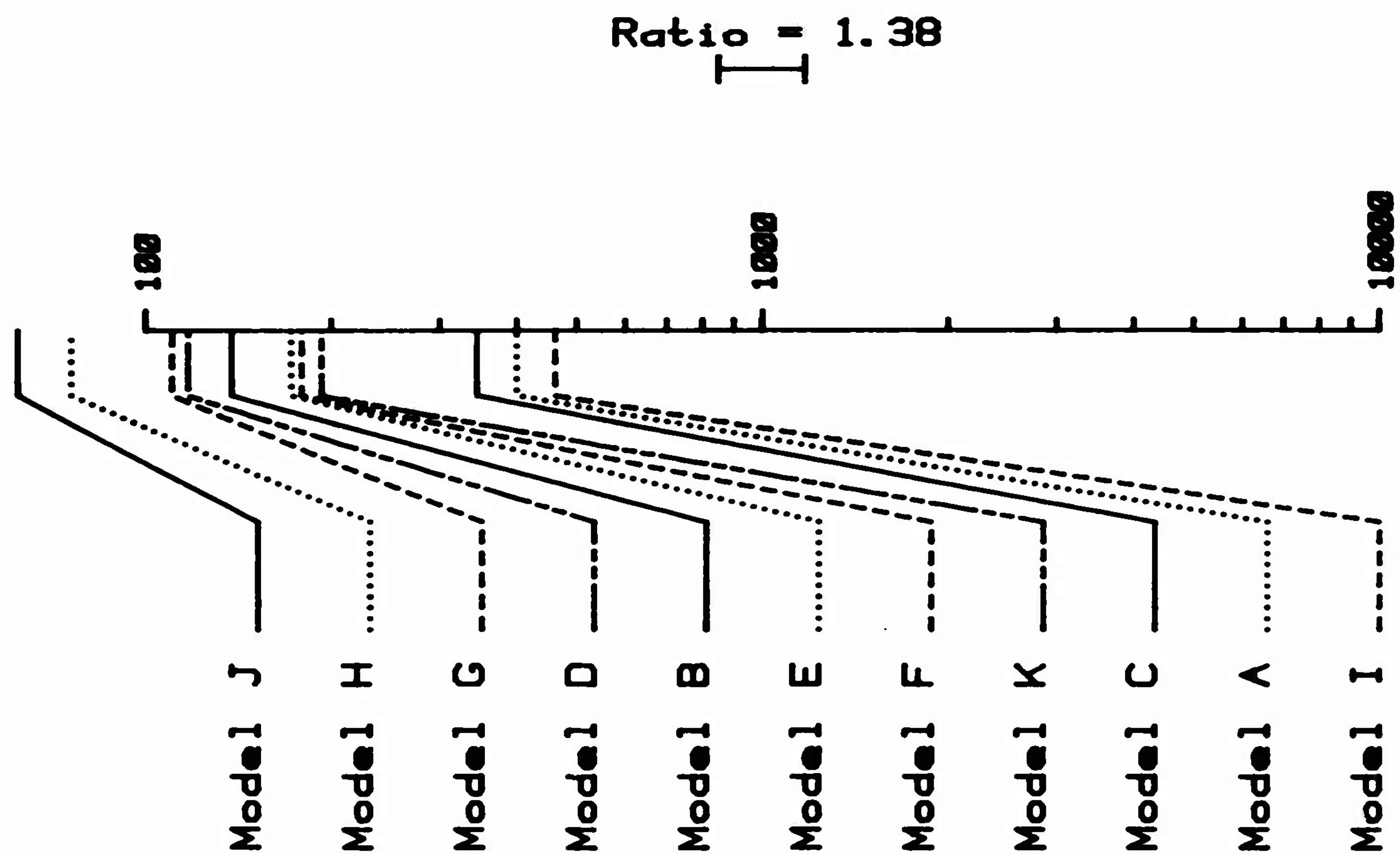


Figure 4B. Comparison of dynamic to static WGV.

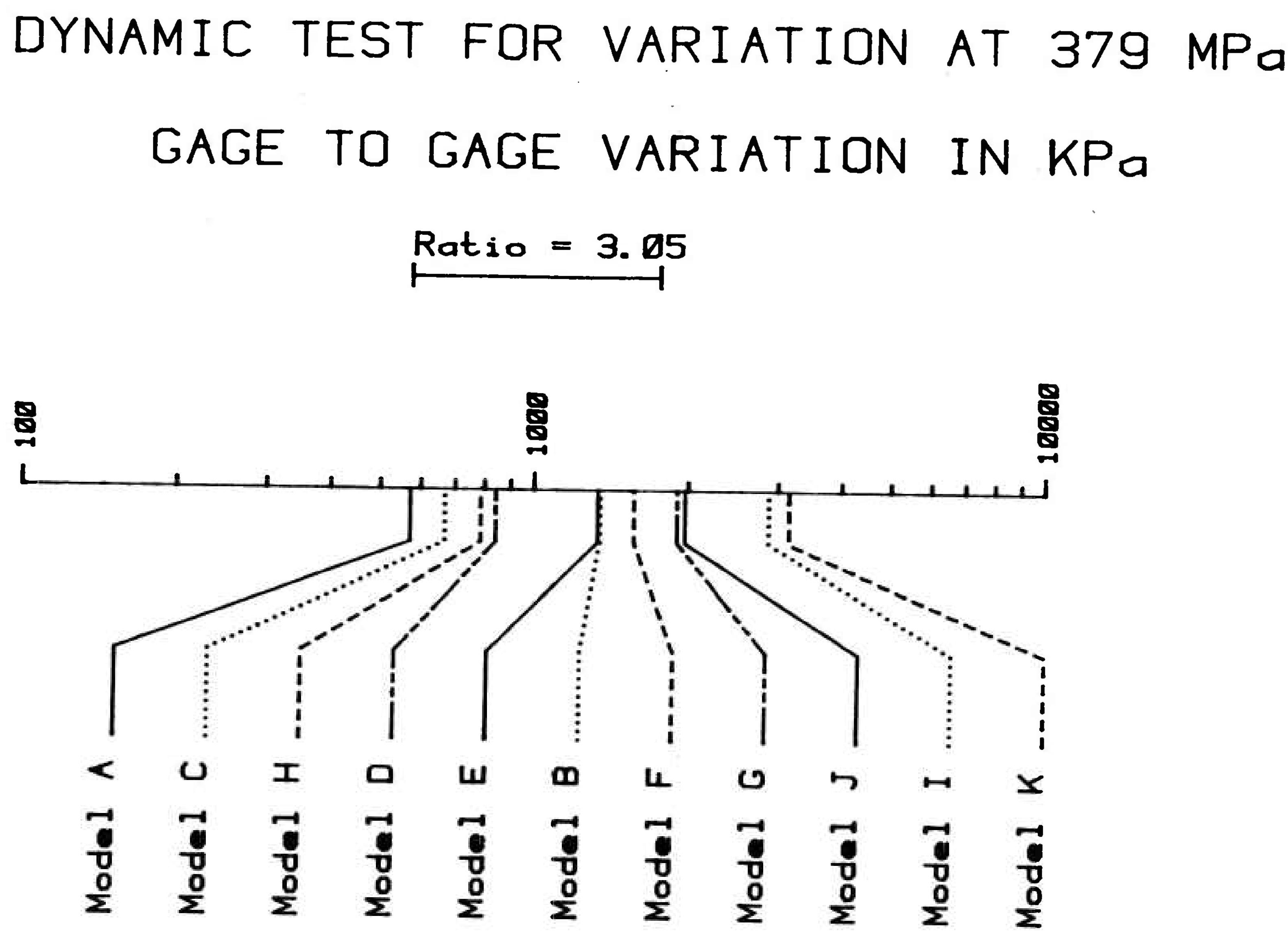


Figure 5A. Comparison of static to dynamic GGV.

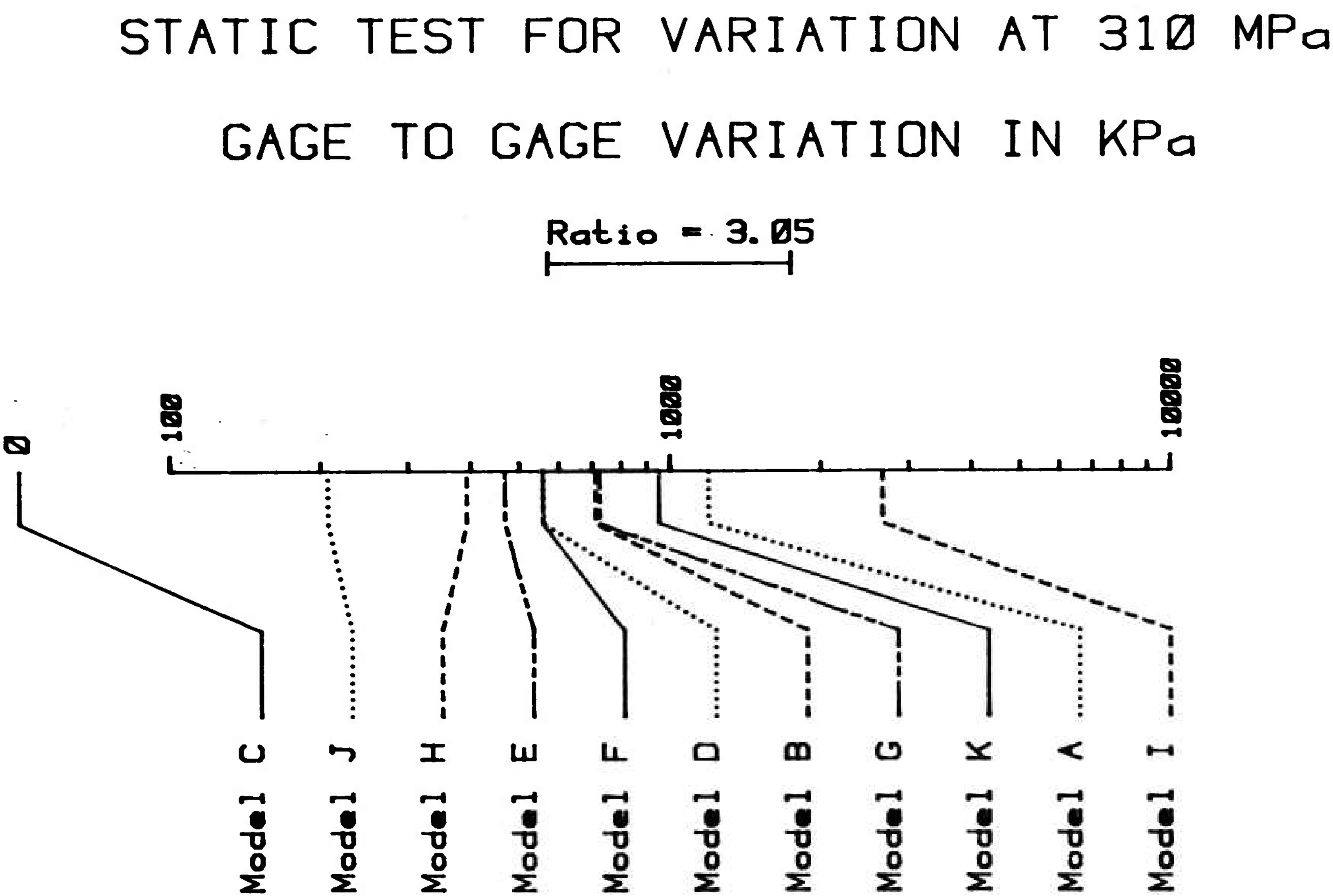


Figure 5B. Comparison of dynamic to static GGV.

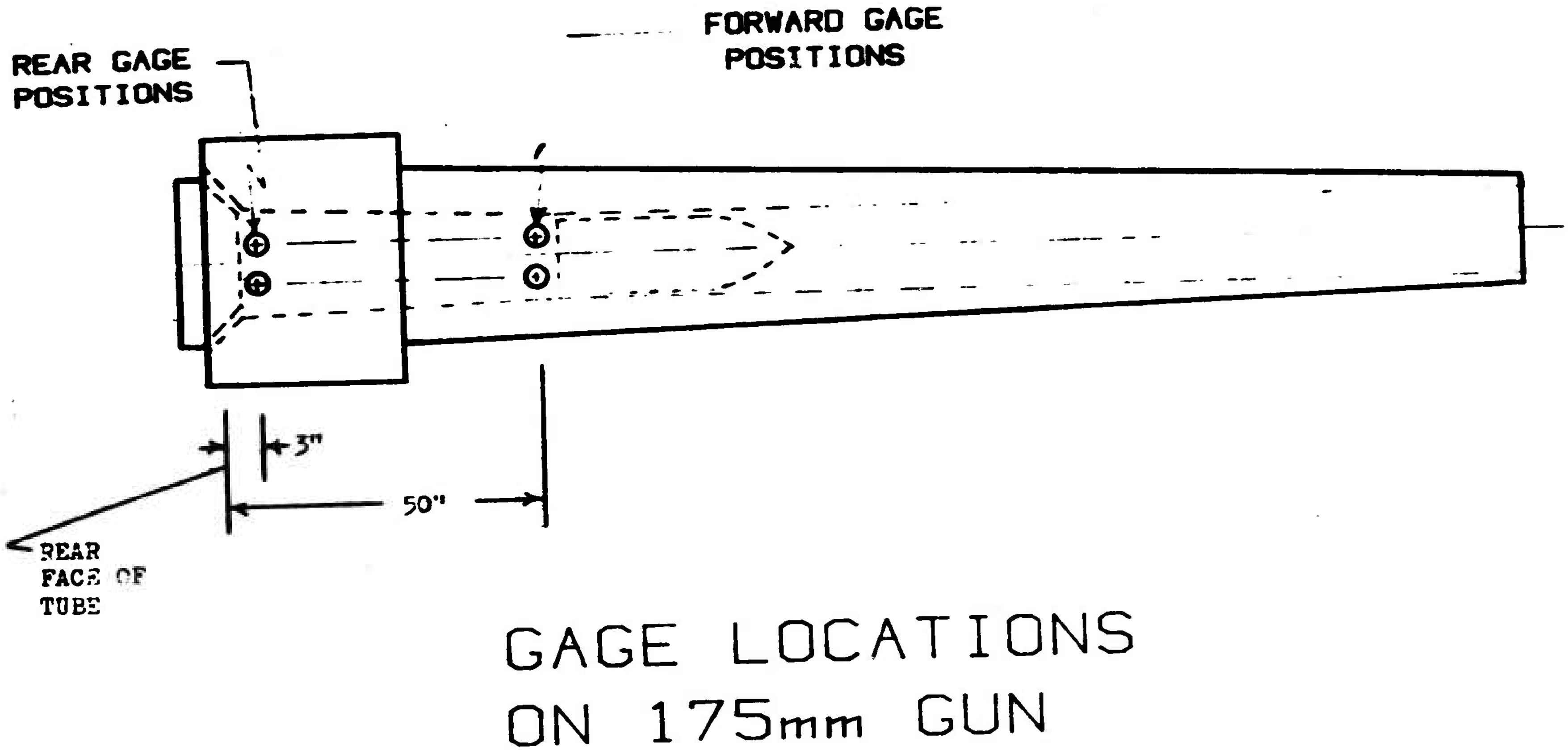


Figure 6. Location of transducers for field testing.

HYDRODYNAMIC GENERATOR TEST FOR BIAS

TREATMENT EFFECT IN MPa

W = 1.54

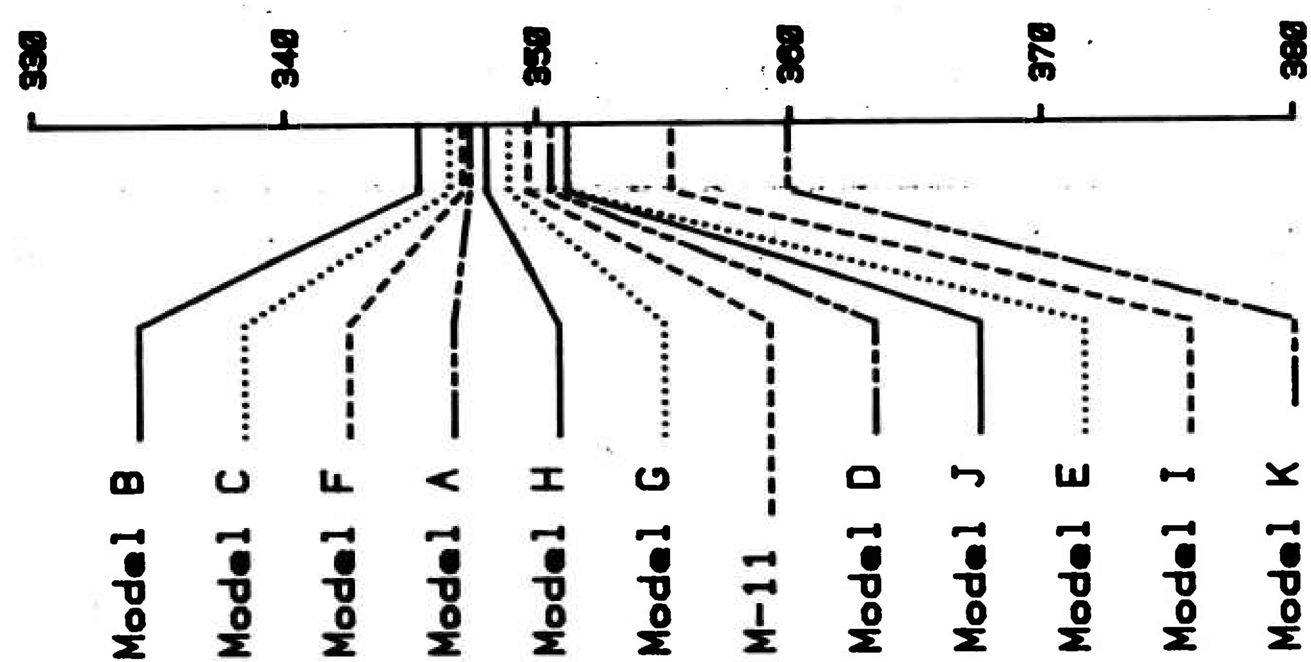


Figure 7A. Graphical summary of bias test data.

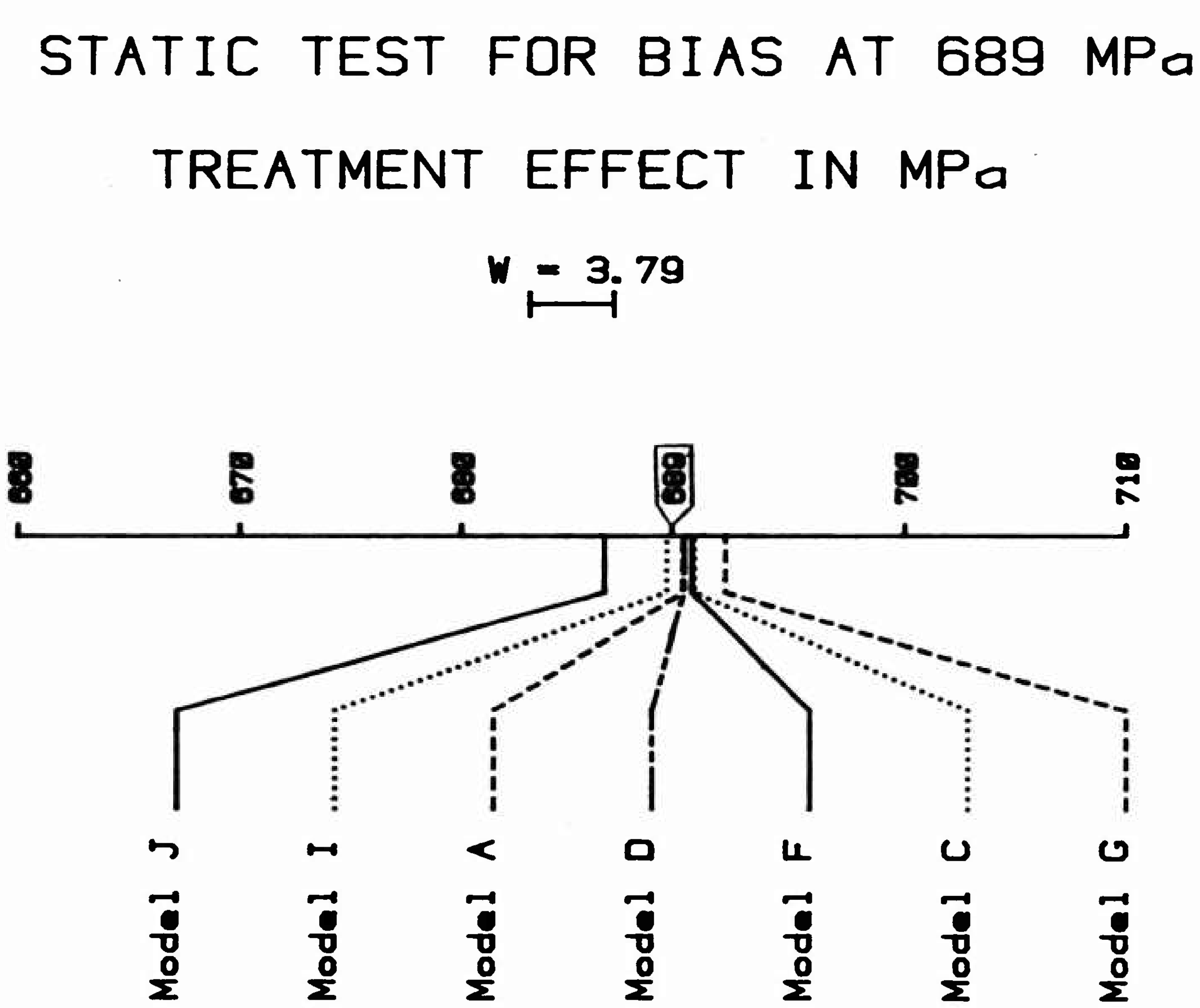


Figure 7B. Graphical summary of bias test data.

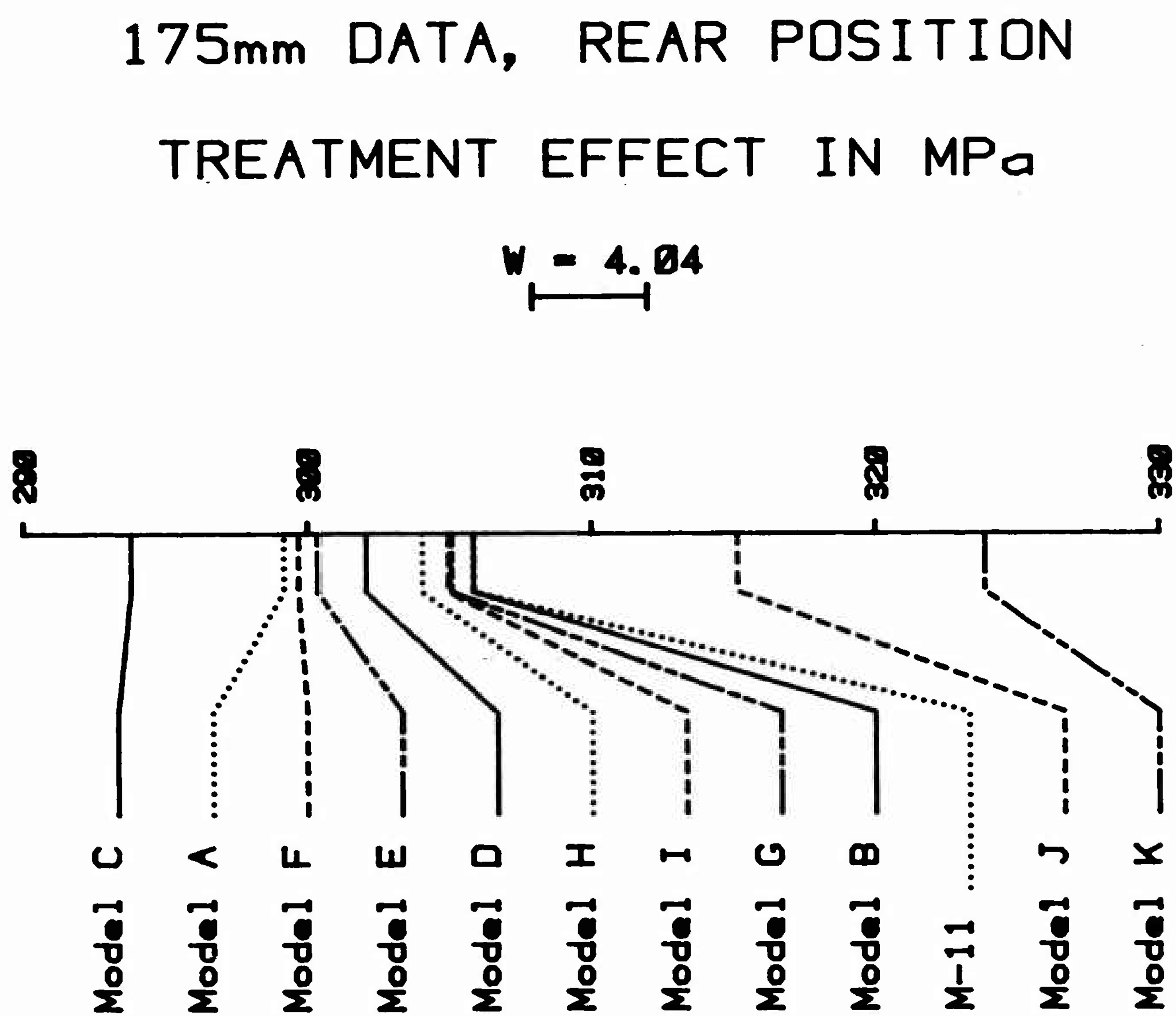


Figure 7C. Graphical summary of bias test data.

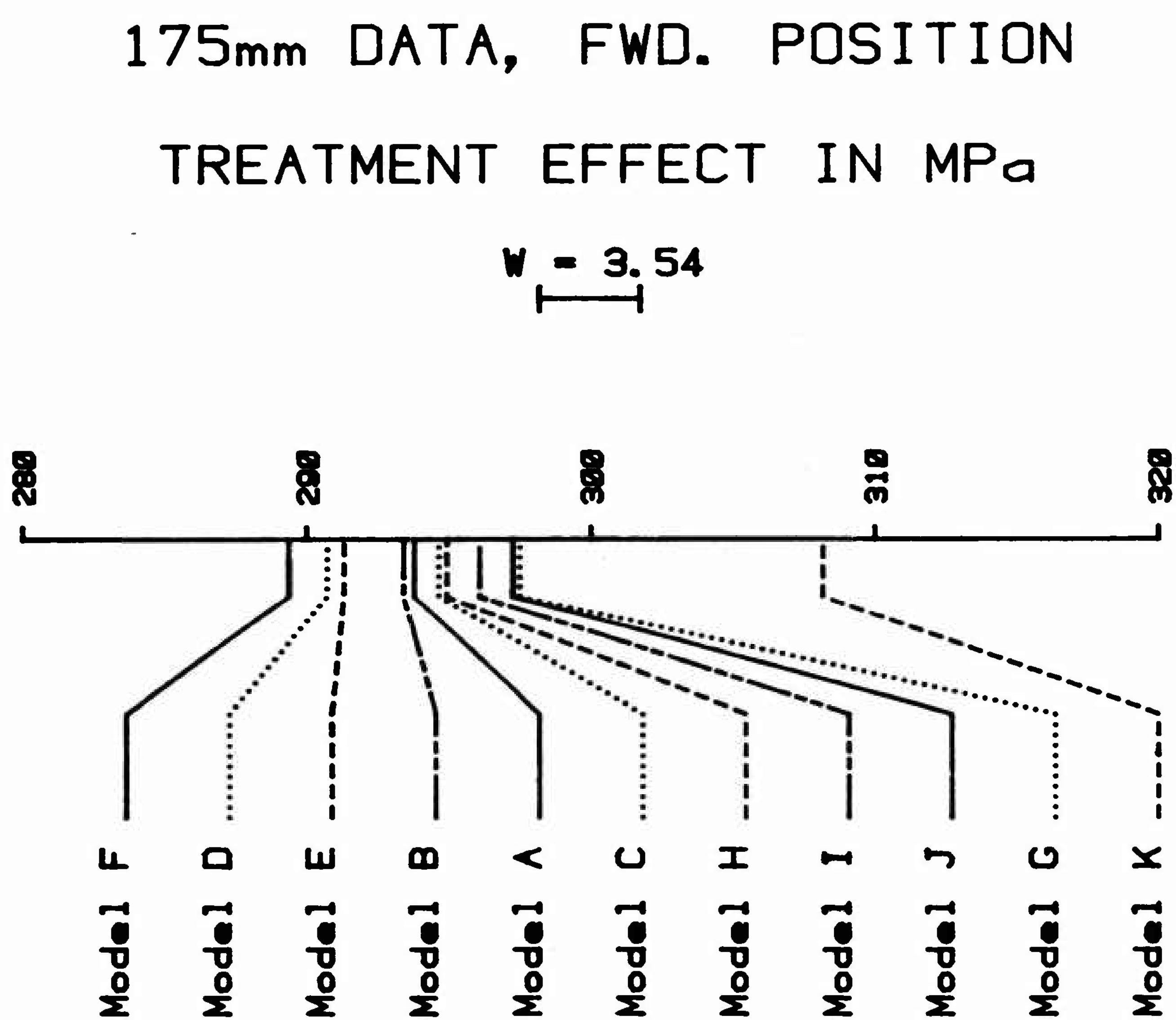


Figure 7D. Graphical summary of bias test data.

STATIC TEST FOR BIAS AT 689 MPa

TREATMENT EFFECT IN MPa

W = 3.79

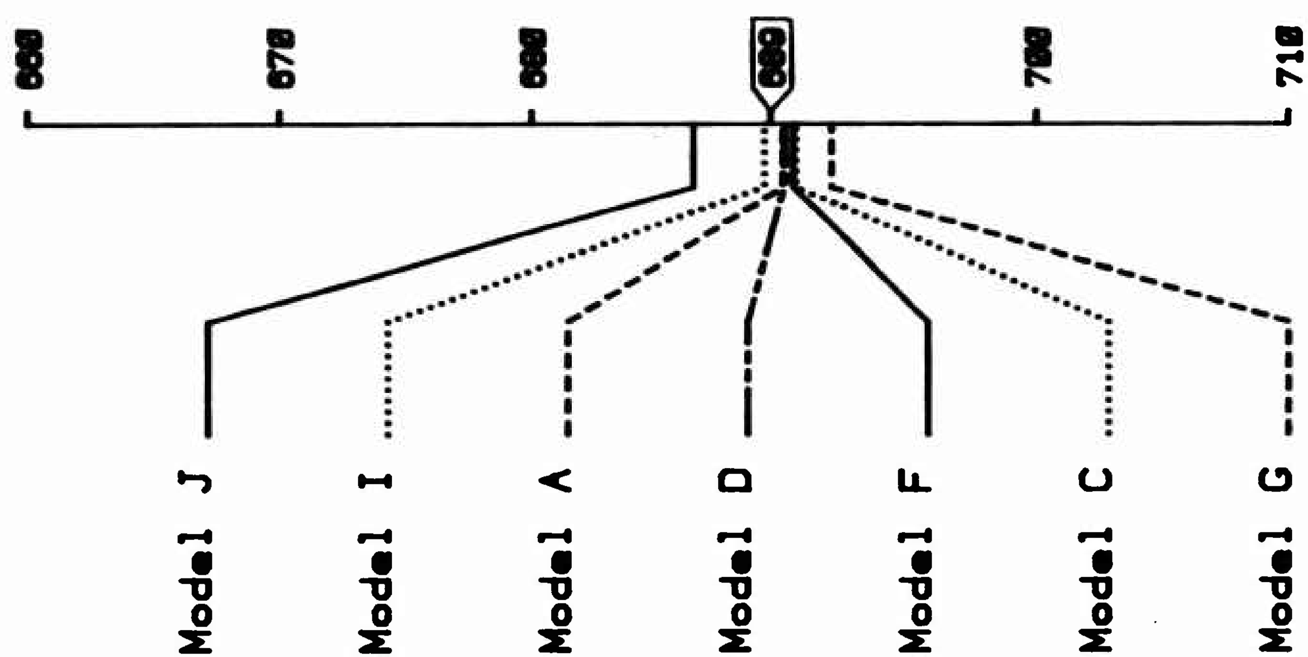


Figure 8A. Graphical summary of high pressure test for bias.

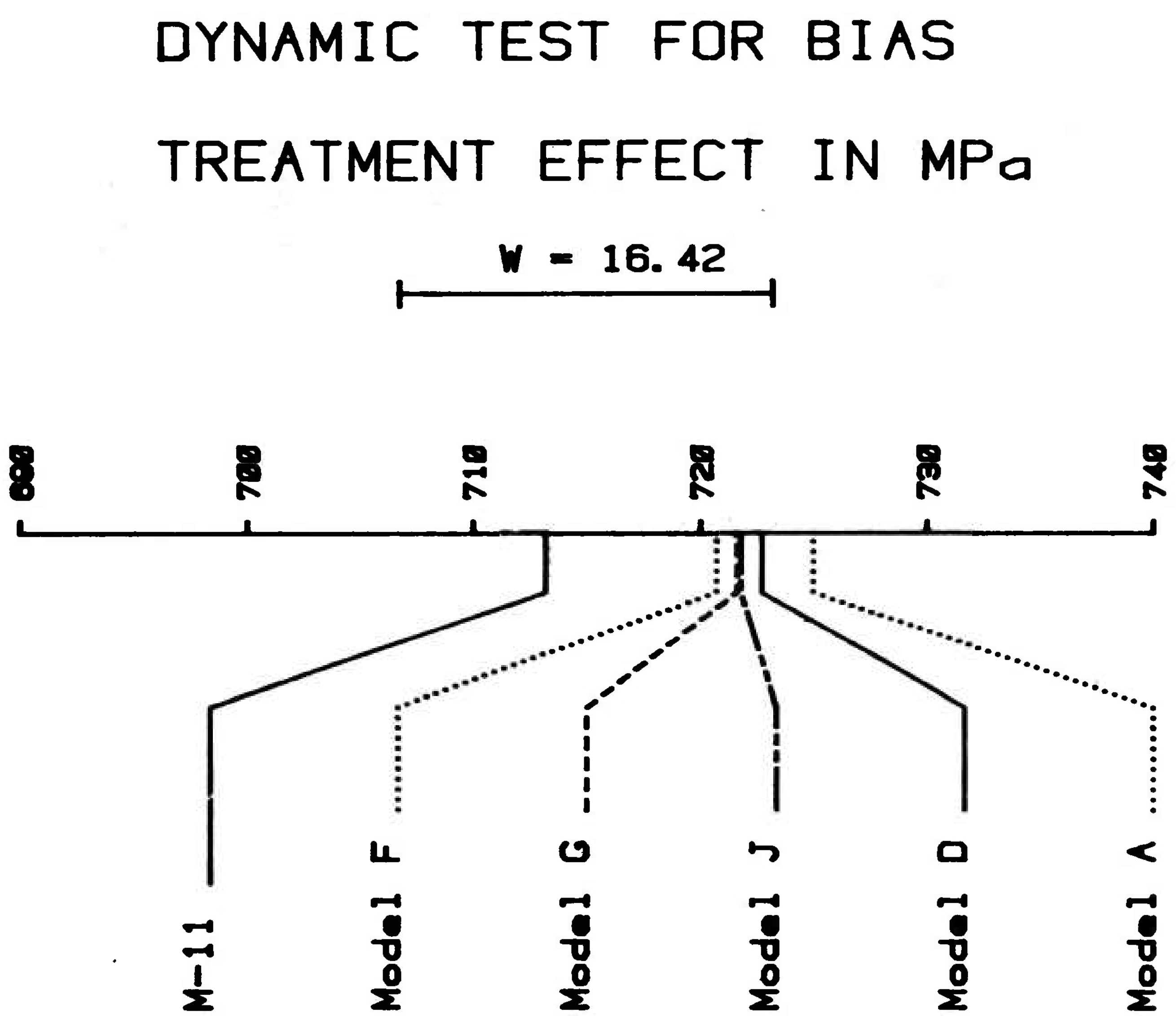


Figure 8B. Graphical summary of high pressure test for bias.

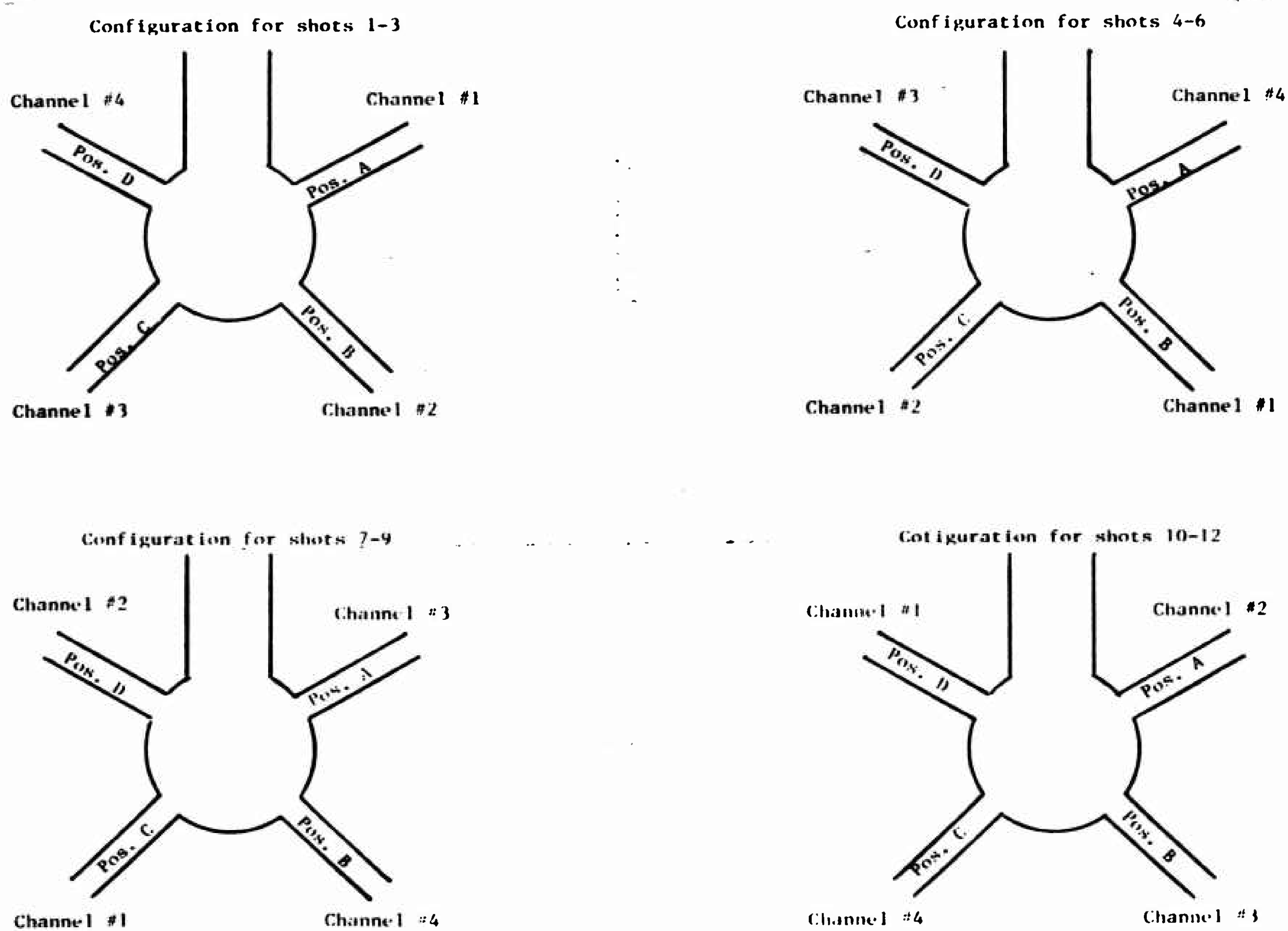


Figure 9. Diagram of the four different mounting configurations used in Latin square test.

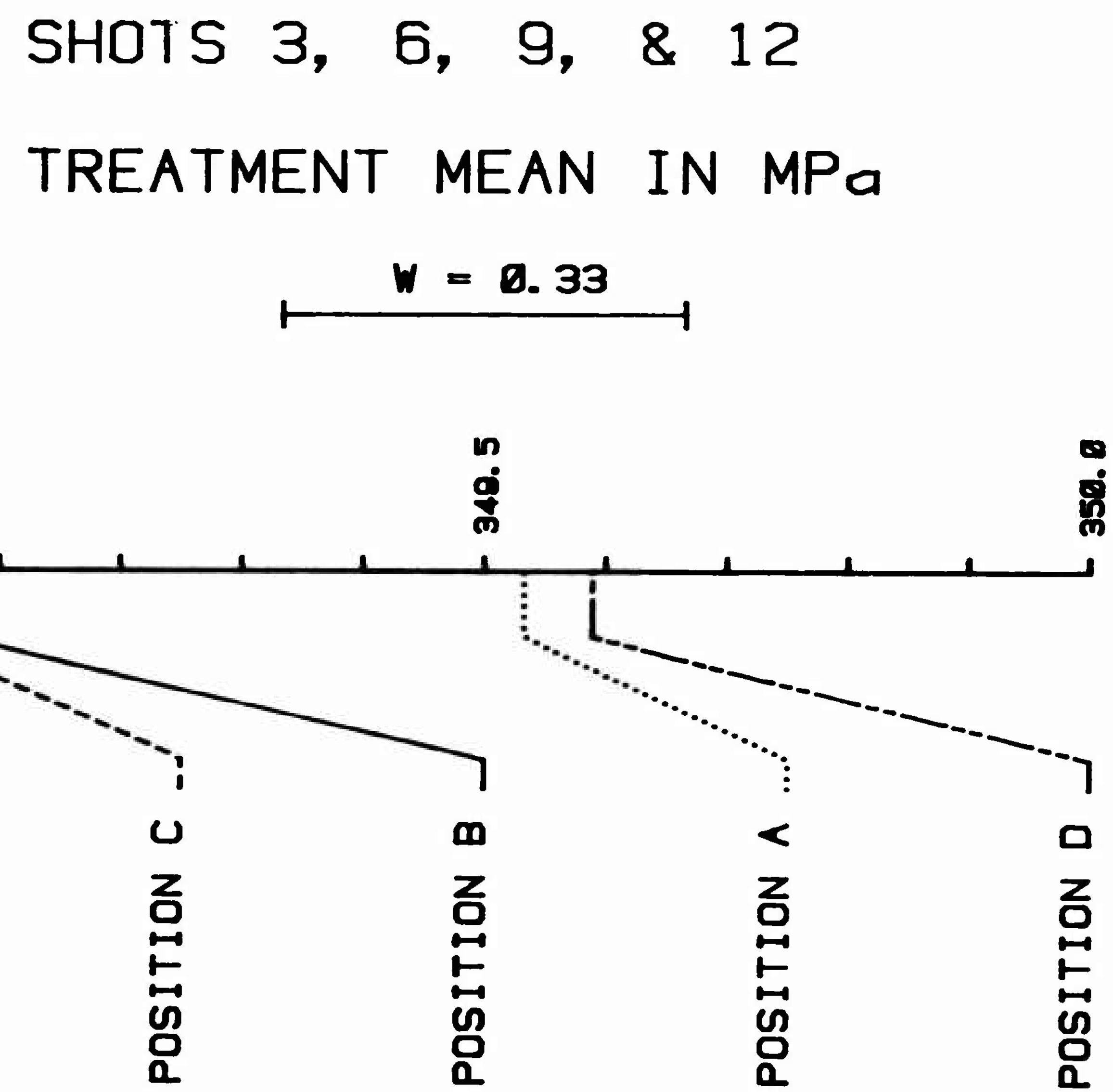


Figure 10A. Comparison of selected groups of shots of the Latin square test.

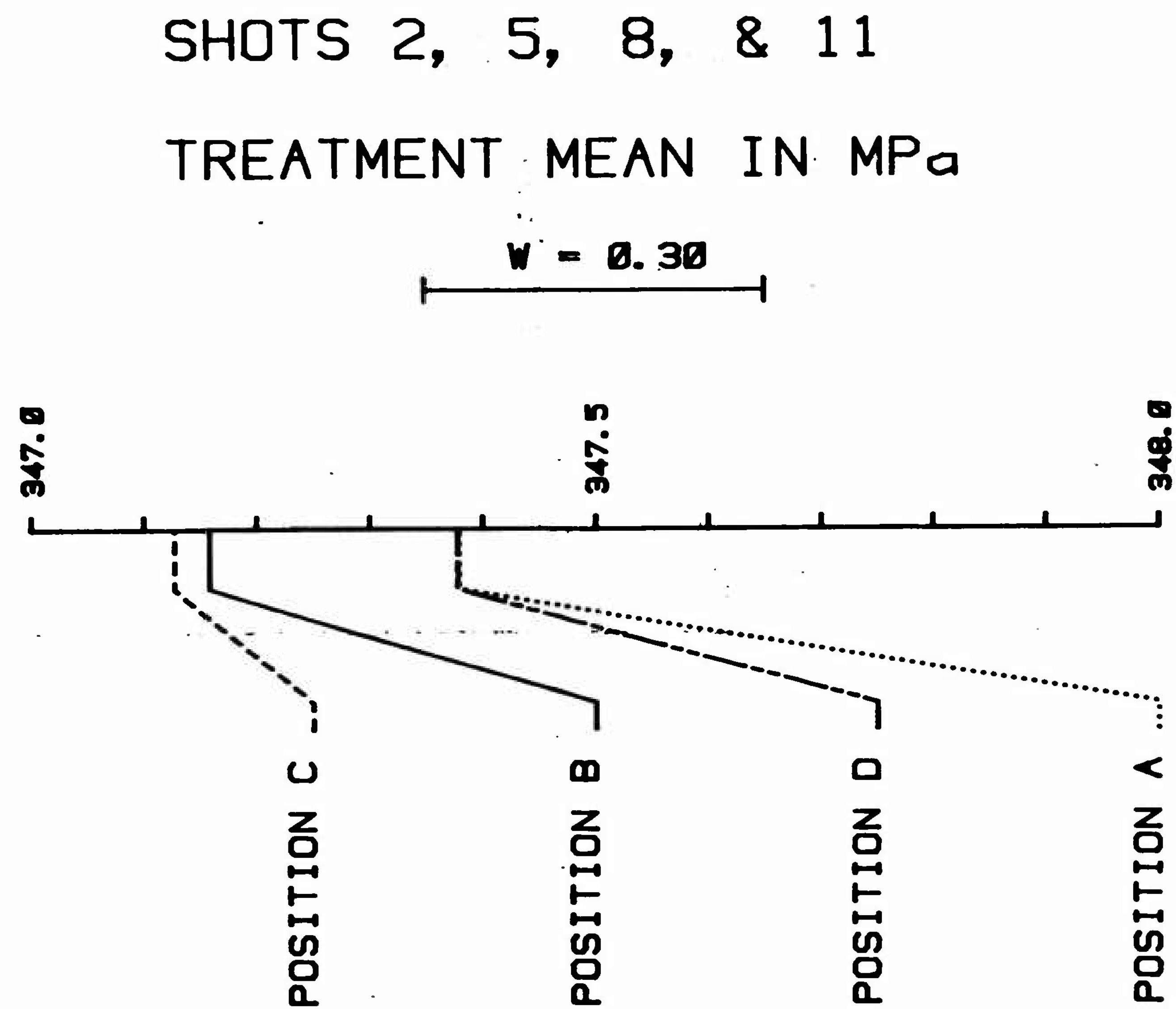


Figure 10B. Comparison of selected groups of shots of the Latin square test.

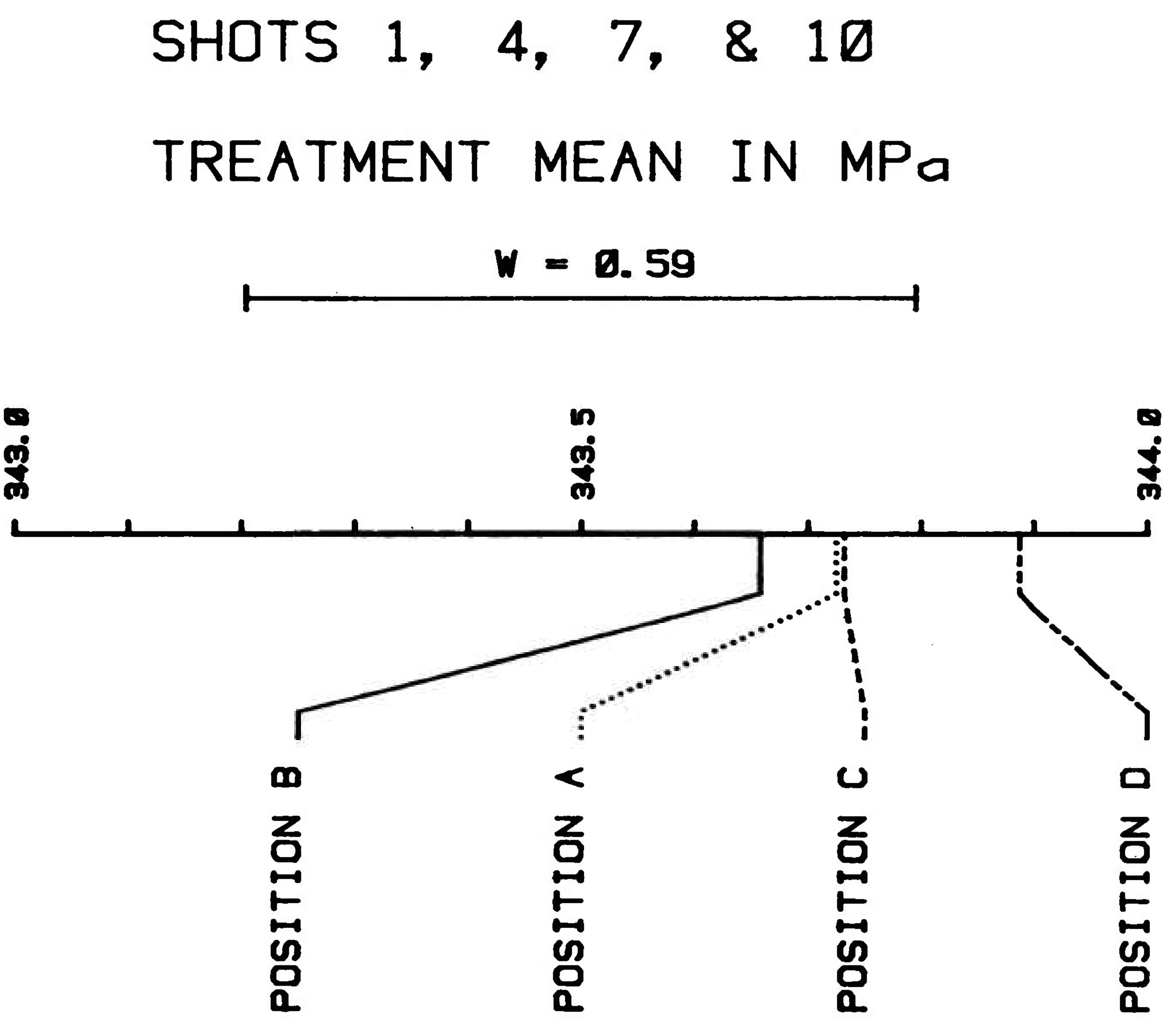


Figure 10C. Comparison of selected groups of shots of the Latin square test.

ACKNOWLEDGEMENT

FOR

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